



# **At the Frontiers of Science**

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**Superconductivity  
and Its Electric  
Power Applications**

# Section I. What is Superconductivity?

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Electricity—it is one of our modern scientific miracles, and today we could not imagine living without it. But what if we could make it better? Superconductivity has the potential to do just that, by improving the capacity, quality,

resistance is something very much like friction. The resistance causes some of the electricity to be lost in the form of heat. Which means that every time you use an appliance, from a radio to a generator, you are not getting 100% of the energy that flows through it; some of it is wasted by the conductor.

Superconductivity—the ability of a material to conduct electricity without losses to resistance—is a physical property inherent to a variety of metals and ceramics, much the same way magnetism is present in a variety of materials. It is dependent on temperature; that is, a material will not exhibit superconductivity until it is sufficiently cold. The necessary temperatures to induce superconductivity are well below what we might commonly consider "cold." They are so low, in fact, that they are measured using the Kelvin temperature scale (K). Absolute zero, or 0 K, is equal to -459° Fahrenheit (°F)! It is defined as the lowest temperature theoretically possible, or the complete absence of heat.

In 1911, working in a laboratory in Holland, the Dutch scientist Heike Kamerlingh Onnes cooled mercury to 4 K (-452°F), almost absolute zero; at this temperature, the motion of individual atoms nearly ceased. Scientists were unsure what effect this extremely low temperature would have on resistance; most

suspected resistance would increase as atomic motion slowed. However, during routine measurements of the mercury, it appeared that there was no electrical resistance! Onnes assumed his equipment was broken, but days later he confirmed that, near absolute zero, mercury did completely lose electrical resistance. Onnes had discovered superconductivity.

## How are superconductors useful?

Superconductors have several pronounced advantages compared to conventional conductors such as copper or aluminum wires: they can carry much higher currents, create vastly larger magnetic fields, and carry electric current with no energy loss to resistance.

Electric power applications that now use conventional copper and aluminum wire—such as motors, generators, transmission cables, and transformers—will benefit from this exciting new technology. Superconducting motors, transformers, and other applications using high-temperature superconducting wire will be half the size of conventional machines with the same power rating, and have half the energy losses. This will be enormously beneficial to the way electricity is generated, delivered, and used.

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and reliability of products that use electricity. There has been a great deal of discussion about superconductivity in the last 10 years, but what exactly is it? In this document you will learn the definition of superconductivity, how it works, and its present and potential uses. You will also get an inside look at the challenges that scientists around the world are working to overcome in order to fully incorporate superconductivity in our everyday lives.

When you turn on a lamp at home, the electric current flows—is conducted—through a wire made of copper or aluminum. Along the way, this wire resists the flow of electricity, and this

the ability of a material to conduct electricity without losses to resistance.

# Superconductivity

## If superconductivity has been around since 1911, why aren't we already using it?

Although scientists were tantalized by the potential of Onnes' discovery, practical applications for superconductors have seemed, until recently, extremely elusive. The major obstacle to their use has been operating temperature. Prior to the mid-1980s, all known superconductors were normally operated below 27 K (-411°F), and thus are called low-temperature superconductors (LTS). These low operating temperatures, which are difficult and expensive to create and maintain, limited superconductors to use in highly specialized applications. For instance, Magnetic Resonance Imaging (MRI) is a commonly used diagnostic technique that gives doctors an unprecedented view of the internal functioning of the human body, without even the smallest incision. MRI relies on extremely strong magnetic fields that were not commonly used until superconducting magnets—smaller, stronger, and more efficient than conventional electromagnets—became commercially available. Before the advent of MRI technology, doctors often had to conduct exploratory surgery to accurately diagnose many medical conditions.

Nuclear Magnetic Resonance (NMR) devices, which are the chemical industry's equivalent of MRI machines, use LTS technology to "see" tiny amounts of chemicals, and can be used to "sniff" tiny amounts of explosives. These are valuable applications for the



Intermagmetics General Corporation/PIX01621

**MRI machines, made possible with superconducting magnets, allow doctors an unprecedented internal view of the human body.**

pharmaceutical and chemical industries. Superconductors also play a key role in scientific research. Particle accelerators, the large instruments that are helping scientists unlock the innermost secrets of the atom, rely on superconducting magnets.

## Why are so many people excited about superconductivity?

Scientific theories had predicted that 30 K (-406°F) was the highest possible temperature for superconductivity, but these theories were shattered in 1986. Researchers at IBM's laboratory in Switzerland had discovered a family of ceramic and oxide materials that superconduct at temperatures much higher than the conventional LTS used in MRI machines and particle accelerators. Within two years, ceramic superconductors that were

superconducting at 125 K (-235°F) had been discovered! At these relatively high temperatures, vastly cheaper and simpler cooling systems—based on commercially available refrigeration practices—made many new applications possible. **Figure 1** shows the rapid discovery of many of these new superconductors around the world.

Electrical equipment, devices, and systems that would have been too costly to purchase and operate at LTS temperatures were now within the realm of possibility. Known as high-temperature superconductors (HTS), these materials set scientists and engineers around the world racing to create systems and devices based on HTS.



**1908**

Dutch physicist Heike Kamerlingh Onnes becomes the first scientist to liquefy helium at 4.2 Kelvin, the temperature of outer space.

**1933**

In their Berlin lab, Walter Meissner and Robert Ochsenfeld observe that superconductors have special magnetic properties in addition to their electrical ones. Specifically, they form a perfect magnetic shield that repels magnetic fields.

**1957**

Three Americans -- John Bardeen, Leon Cooper, and Robert Schrieffer -- propound a comprehensive theory on the microscopic mechanism at work in superconductivity. The Bardeen, Cooper, and Schrieffer theory explains how negatively charged electrons that normally repel each other are, in superconductors, drawn together through interactions with phonons, or vibrations in the atomic lattice. The theory is considered one of the landmarks in 20th century theoretical physics, and 15 years later the three Americans are awarded a Nobel Prize.



## Superconductor Timeline

**1911**

Studying electrical properties in metals at low temperatures, Onnes becomes the first to observe the complete absence of resistance. Experimenting with mercury cooled by liquid helium, Onnes names the phenomenon superconductivity. Over the next two decades, superconductivity would be demonstrated in 11 elements and 50 compounds and alloys.

**1950**

Theoretical physicists all over the world, including Albert Einstein, puzzle over superconductors and the mysteries of their electrical and magnetic properties. Russians Vitaly Ginzburg and Lev Landau develop a theory using quantum mechanics to explain the electrodynamic behavior of superconductivity.



American Superconductor Corporation/PIX01600

**Figure 1. Superconductor Timeline — The discovery of superconductors has been of worldwide interest throughout the 20th Century.**

**Electromagnetic coils based on HTS wire are used in motors, generators, transformers, and other electrical equipment.**

**1962**

English physicist Brian Josephson predicts the “tunneling” phenomenon in which pairs of electrons can pass through a thin insulating strip between superconductors. So-called Josephson junctions are developed quickly and eventually find use in electronic measuring devices that exploit the junctions’ sensitivity to magnetic fields.

**1972**

The Japanese test their first magnetically levitated (maglev) rail vehicle using a niobium-titanium superconductor. The maglev rail project mushrooms over the next two decades as railway officials dedicate themselves to the goal of producing a frictionless train that can go from Osaka to Tokyo, a distance of 343 miles, in one hour.

**1986**

Alex Müller and Georg Bednorz, IBM scientists in Zurich, announce a ceramic compound that is superconducting at the unheard-of temperature of 35 Kelvin. Müller and Bednorz later win the Nobel Prize for this discovery.

**1988**

Further copper oxide variations are discovered. A compound containing bismuth is revealed by Japanese scientists. This will prove essential for the development of high-temperature superconducting (HTS) wire. A version using thallium is produced at the University of Arkansas that will prove important to use in thin-film applications in electronic devices. Several small American companies are started to try to exploit the new superconductors.

**1961**

A practical metal wire made of niobium and tin is developed that becomes superconducting when cooled with liquid helium. Later, an improved wire of niobium and titanium is developed. Both superconducting wires are used in research, medicine, and industry.

**1968**

IBM embarks on a project to build a Josephson junction computer. Over the next 15 years, Japanese firms including Hitachi and Fujitsu, also work on the technology.

**1982**

The first MRI machines are placed in hospitals for testing. MRIs use superconducting wires that create a powerful magnetic field. The machines are considered the most significant imaging device since the X-ray.

**1987**

At the University of Houston, Paul Chu announces a variation on the Müller-Bednorz copper oxide compound that becomes superconducting at an astonishing 94 Kelvin. The material can be cooled by cheap and readily available liquid nitrogen.

**1996**

U.S. researchers break world records by demonstrating a 200-horsepower motor and a 2.4-kilovolt current limiter based on HTS. A 50-meter HTS transmission line is also built.

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High-temperature superconductivity promises more efficient and powerful devices, perhaps beyond any dreamed of today. LTS technology has already given us exciting, novel, and highly valuable applications that have improved our quality of life; the possibilities for HTS are practically limitless. Although difficult hurdles remain, today we are close to seeing practical electric power devices and energy systems based

on HTS technology. The next decade may witness the perfection of a variety of superconducting manufacturing techniques and the introduction of products incorporating HTS technology. While we can't predict where superconducting technology might lead us, we can say with certainty it will be an exciting journey.■

## Section II. The Physics Behind the Phenomenon

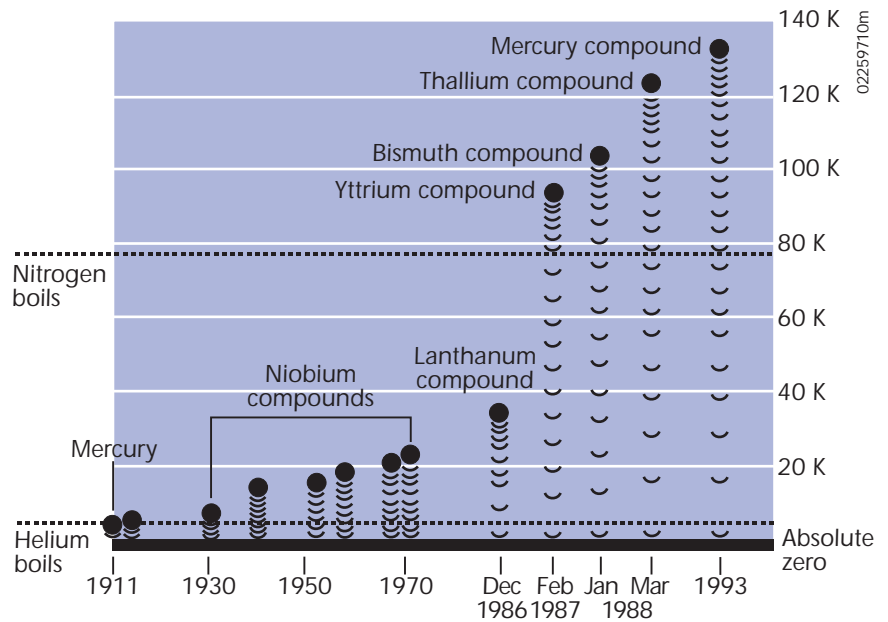
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The physics behind superconductivity baffled scientists for decades. In fact, almost 50 years passed between the discovery of superconductivity and the publication of the Nobel prize-winning theory developed by John Bardeen, Leon Cooper, and Robert Schrieffer, which describes the fundamental mechanisms at work in LTS.

Today, many important questions about how and why certain materials exhibit superconductivity remain unanswered, especially in the relatively young field of HTS. Although the more sublime aspects of the phenomenon continue to elude researchers, superconductivity's basic principles are well understood. In this section, we discuss these basic principles and the challenges associated with optimizing a superconductor's performance.

### What are the basic principles of superconductivity?

The temperature at which a material becomes superconducting is known as the transition, or critical, temperature ( $T_c$ ), and it varies for different materials. The first identified superconductor, mercury, was discovered in 1911 by Heike Kamerlingh Onnes. It has a  $T_c$  of 4 K (-452°F). More than 15,000 metals and metal alloys that are superconducting under certain temperatures and pressures were discovered during the next 50 years, but until the discovery of HTS, none had a  $T_c$  above 30 K (-406°F). **Figure 2** shows the  $T_c$  for a variety of widely used superconductors, ranging from close to absolute zero to as high as 135 K (-217°F).



**Figure 2. Critical Temperatures—The temperature at which a material becomes superconducting varies depending on the material. Critical temperatures range from close to absolute zero to nearly 135 K (-217°F), and have increased over the years as new compounds have been discovered.**

In addition to temperature, a material's ability to superconduct depends heavily on two other variables. Superconductors operate in magnetic fields, but there is a field strength beyond which superconductivity is lost. This is known as the critical magnetic field. The maximum current that a superconductor can carry is called the critical current. If any of these "critical" factors—temperature, magnetic field strength, or amount of current—is exceeded, superconductivity is destroyed. The challenge is to design systems and devices that can operate under the "ceiling" set by these three variables.

### What makes superconductivity possible?

All materials are made up of atoms, which contain electrons. If the atoms of the material are

uniformly lined up over long distances, it is said to have a "crystalline" microstructure. Both LTS and HTS materials, as well as normal metals like copper and silver, are crystalline. **Figure 3** shows the typical atomic arrangement for this kind of microstructure, called a crystal lattice. Some of the electrons associated with the atoms are free to move through the lattice, creating an electric current.

Above absolute zero, crystal lattices vibrate. In conventional metal conductors, the electric current—made up of randomly moving electrons—flows through the lattice. Occasional interactions with the vibrations or with lattice imperfections cause the flowing stream of electrons to lose energy in the form of heat; this is the phenomenon we know as electrical resistance, and it causes energy loss.

# The Physics

superconductivity only exists below certain critical values of temperature, magnetic field, and current.

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In superconductors, however, electrons act very differently. At extremely low temperatures the electrons pair up and move in the lattice, without interacting with any of the vibrations, and, consequently, without losing any energy to resistance. This lack of energy loss is the great advantage of superconductivity.

In highly resistive materials, the lattice heats up a lot as current flows through it. Many electrical appliances, such as toasters, operate on this basis. When the toaster is on, electrons flow

through a wire (lattice) that resists the electric current, heats up, and then radiates this heat, toasting the slices of bread. In this example, of course, heat production is the object of the appliance.

## What forms do superconducting materials take?

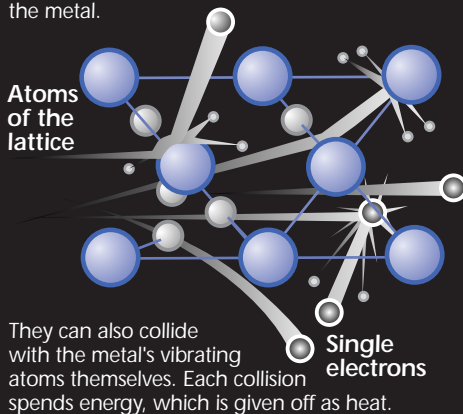
Superconducting materials are generally made into wires or films. They can also be made into monolithic (single-component) objects.

Ceramic-based superconducting wires, usually manufactured using conventional wire drawing and rolling equipment, are used to make electric power devices like magnets, cables, and other electrical equipment. Wires are moderately expensive to make.

Superconducting films are coatings, typically manufactured using vacuum-based equipment, and are the basis for electronic devices such as communications filters and magnetic field sensors. Films generally have the highest

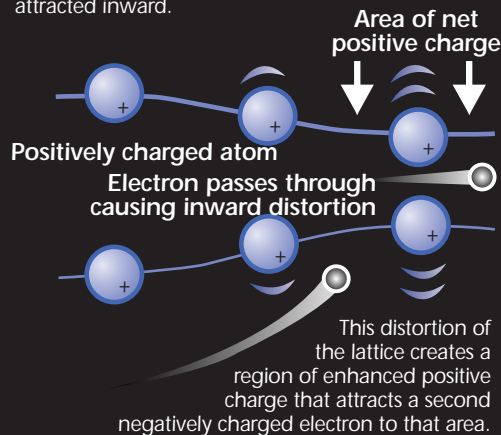
### Normal state

Normally, an electric current is composed of single electrons, and resistance occurs as these electrons collide with small impurities and defects in the latticelike architecture of the metal.

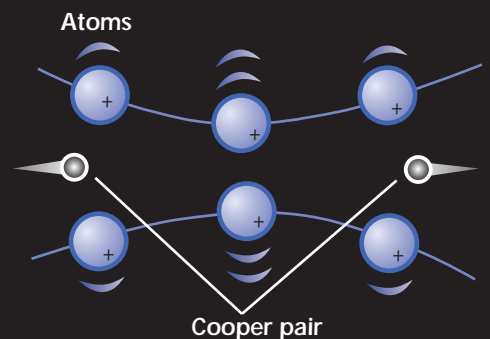


### Superconductive state

With superconductivity, as a negatively charged electron passes between the metal's positively charged atoms in the lattice, the atoms are attracted inward.



Second electron is indirectly bound to the first creating a Cooper pair.



**Figure 3. Superconductive State—In superconductors, electrons pair up and travel without interacting with vibrations of the crystal lattice and, consequently, without losing energy to resistance.**



American Superconductor Corporation/PIX01604

**Superconducting wire development today focuses on increasing the amount of current that can flow through a wire. Wires are used to make electric power equipment including motors and cables.**

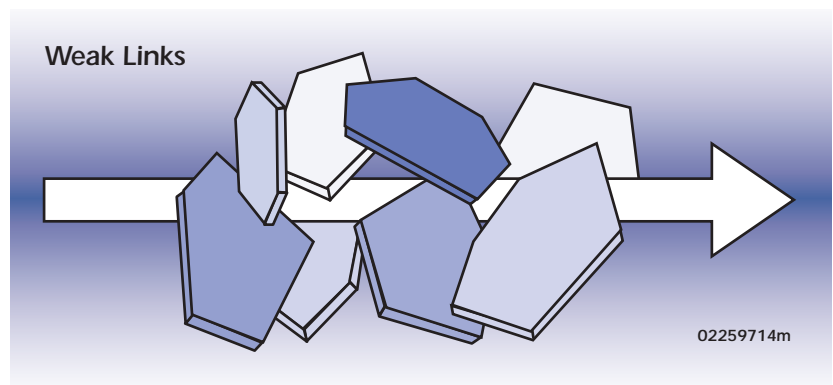
## Do superconductors have any unique problems?

The superconducting material's crystalline structure determines its performance level: the more uniform or perfect the structure, the better the current-carrying capability. We can think of the lattice as an interstate highway with an unimpeded traffic (current) flow. As mentioned earlier, film superconductors have uniform, continuous lattices that enable current to flow very efficiently through a single crystal. The superconducting material in HTS wires and monoliths, on the other hand, is made up of countless individual crystals, or "grains," in close contact with each other. The current flows from grain to grain as it moves through the material, but not as smoothly as in the highly aligned films. If adjacent grains do not line up properly, or if there are impurities (nonsuperconducting materials) between them, the flow of electrons is impeded. This flow resembles a bumper-car track, in which repeated collisions prevent the

current-carrying capabilities and are the most expensive to make.

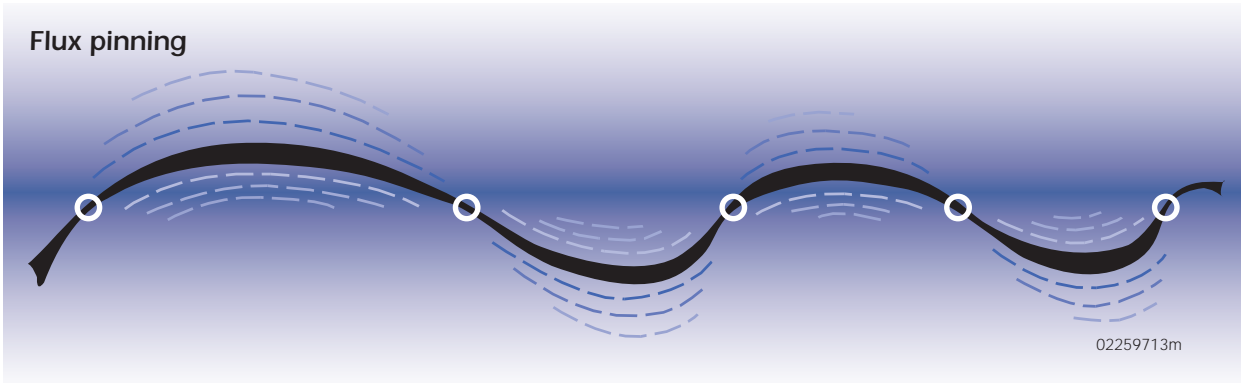
Monolithic superconducting objects are typically created from compacted powder that is formed into the desired shape. Examples might be frictionless bearings. Monoliths are the least expensive to make.

HTS wires and the electric power applications that can benefit from superconducting wire technology are the focus of this document.



**Figure 4. Weak Links — If individual crystals in HTS materials do not line up properly, the flow of electrons is impeded. Poor crystal interface is called a "weak link."**





**Figure 5. Flux Pinning — If magnetic field lines drift freely, energy is lost and performance is lowered. Therefore, HTS wires must be able to hold magnetic field lines in place, a phenomenon known as flux pinning.**

cars from getting anywhere quickly. Poor grain interface, as shown in **Figure 4**, is called a "weak link."

HTS wires must also be able to hold magnetic field lines in place, a phenomenon illustrated in **Figure 5** and known as "flux

pinning." If the magnetic field lines drift freely, energy is lost and performance is lowered. The HTS wires being manufactured today have poor flux-pinning properties and must be used at low temperatures or low magnetic fields to achieve high currents.

Understandably, researchers today are focusing on eliminating weak links and producing strong flux-pinning centers. They hope to improve the performance of superconducting wires and monoliths by incorporating film manufacturing techniques.■

### Are superconducting materials easy to work with?

Niobium titanium is the standard LTS material for existing applications such as MRI machines and particle accelerators. Over the years, even before the discovery of HTS, researchers discovered several other LTS compounds that operated at higher temperatures and created stronger magnetic fields than niobium titanium, but they all had one crucial drawback—they were brittle and difficult to manufacture. Regardless of how well these materials performed in the laboratory, they were not commercially viable because they could not be economically manufactured.

With the advent of HTS technology, scientists have dramatically improved operating temperature, but manufacturing ceramic-based HTS wire has its own difficulties. Imagine trying to make strong, flexible wire out of materials that are as brittle as blown glass. The chemistry of HTS compounds is as complex and process-sensitive as that of any material currently used in large-scale manufacturing.

Three different superconducting compound families currently show the most promise in HTS applications. They are comprised of four to seven chemical elements, and are referred to by one element—either yttrium, bismuth, or thallium—for short.

### How is wire made from ceramic superconductors?

Soon after HTS materials were discovered, researchers began experimenting with many novel wire-making methods. By 1995, two manufacturing techniques showed the greatest potential for producing high-performance HTS wire at low cost: the oxide-powder-in-tube (OPIT) and the coated-conductor methods. The OPIT method has been the most useful because of its applicability to high-production manufacturing. Coated conductors promise higher performance and lower costs than OPIT and will likely be perfected during the next 5 to 10 years. Once a manufacturing process is developed, coated conductors, which have many of the benefits of superconducting films, will probably become the wire of choice for future systems.

The OPIT and coated-conductor processes have one common effect: they create "texture" in the final superconductor. Texture refers to the orientation of the material's crystal lattice. In materials with excellent texture, the grains and particles are uniformly aligned, acting as a single crystal, which allows current to flow unimpeded.

OPIT processing relies on rolling techniques to produce texture in the final wire. Coated-conductor techniques incorporate layers of material on flat tapes. Certain layers are textured, and this texture is then transferred to any HTS material that is subsequently deposited. While OPIT wires can be made in one-kilometer lengths, coated-conductor wires are much less mature and are being made in laboratories in meter lengths rather than kilometers.

### How does OPIT processing work?

OPIT processing can begin with either metallic or ceramic precursors; currently the process involving ceramic precursors yields wire with the best performance. High-quality HTS wires

# Manufacturing

methods that show the greatest potential are oxide-powder-in-tube and coated-conductor.

manufactured using this method are being produced by several U.S. companies, as well as companies in Japan and Europe, and are used in every HTS prototype being developed.

A preliminary step is the production of HTS precursor powders, accomplished by subjecting the original compounds to a series of heat treatments. This precursor powder is then loaded into a silver cylinder, called a billet, which is welded closed. From this point the billet is processed through a variety of steps; the exact details of which vary and are proprietary from one company to another. Most billet processing techniques are variations of the OPIT process shown in **Figure 6** (page 12).

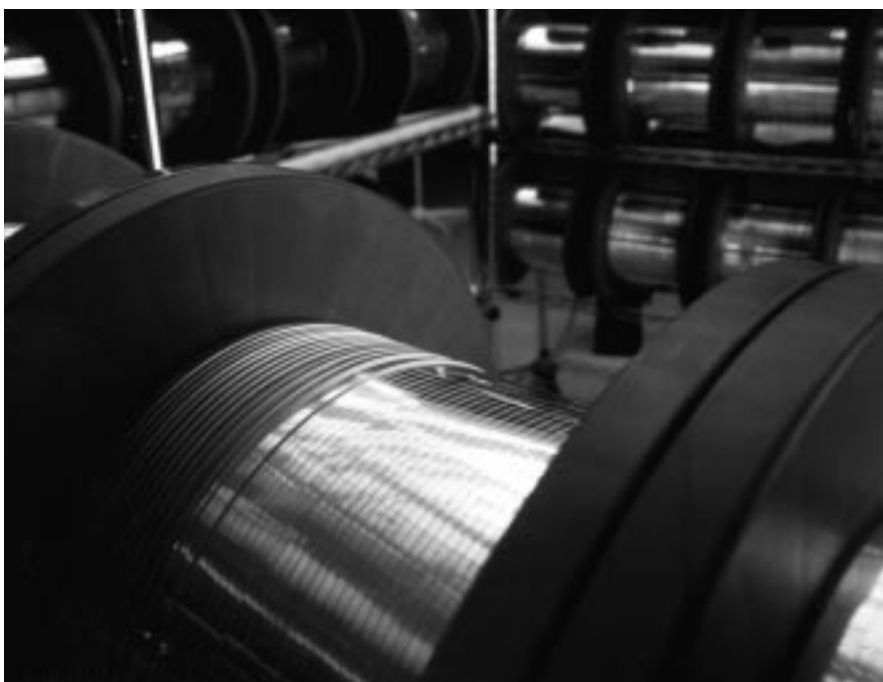
### How does the coated-conductor method work?

The second major wire-making technique borrows heavily from film manufacturing, which produces optimal superconducting properties. However, film manufacturing is a batch process, used for making relatively small sizes. Wire-making is a continuous process. The challenge can be thought of in terms of baking bread: it is fairly easy to make a one-foot loaf of bread in a kitchen oven. But what if you need to bake a 100-foot loaf of bread? How would you do it? A 100-foot oven is prohibitively expensive, just as a 100-foot vacuum chamber for film processing would be impractical.

Although applying film processing techniques to wire making is fraught with difficulties, in the last few years two exciting research discoveries have opened the door to achieving film performance in

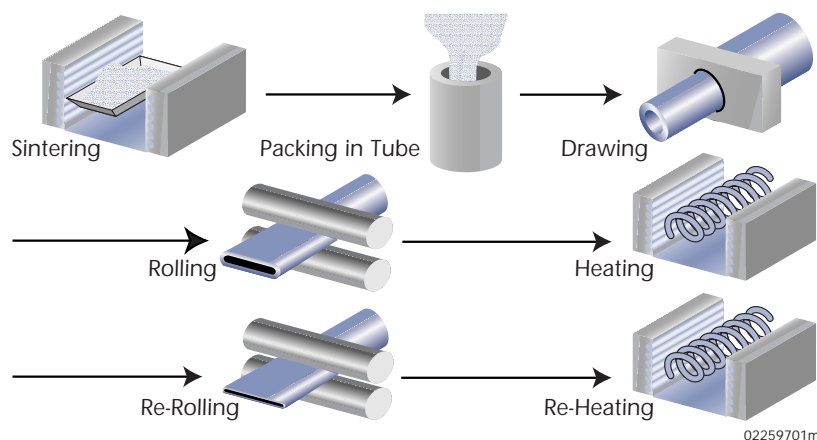


American Superconductor Corporation/PX06101



American Superconductor Corporation/PX06098

**American Superconductor Corporation's HTS wire manufacturing process is capable of repeatedly manufacturing 200-meter lengths of high performance wire.**



**Figure 6. OPIT Process — Most high-temperature superconducting wire considered for use in electric power applications is currently made by the oxide-powder-in-tube method.**

continuous wire-manufacturing processes.

Researchers at Los Alamos National Laboratory (LANL) developed a coated-conductor process known as ion-beam-assisted deposition (IBAD). In this process, a flexible strong tape, or "substrate," is coated with a buffer to chemically protect it from the superconductor layer that is deposited next. The buffer also transfers its crystalline texture to the superconductor. The key to the process is the use of special ion beams to both deposit and orient the buffer. When the superconductor is deposited on top of the buffer layer, a highly aligned film is formed. The aligned, or textured, film has virtually no weak links or other grain interface problems that have typically plagued yttrium- and thallium-based HTS wire development efforts. Current flows easily between aligned grains, resulting in excellent performance. As shown in **Figure 7**, recent tests on laboratory samples demonstrate performance characteristics nearly 50 times better than state-of-the-art bismuth OPIT wires.

The second coated-conductor processing technique is rolling-assisted biaxially-textured substrates (RABiTS). Developed at Oak Ridge National Laboratory (ORNL), the RABiTS process, like the IBAD process, creates an aligned crystalline texture on which to deposit the superconductor. In RABiTS, texture is developed in the metallic-based substrates through proprietary rolling techniques. This texture is then transferred to successive buffer layers and superconductor layers. HTS RABiTS wire samples also have excellent critical current performance. The RABiTS process is appealing to industry because of its low cost and applicability to continuous manufacture.

So far these processes are limited to laboratory scale and short wire lengths, but efforts are underway by industry and the national laboratories to address scaling and manufacturing issues, and to develop cost-effective methods for depositing the buffer layers and superconductors.

## What are the engineering issues?

Superconductor devices have many common design issues, which will likely be solved differently for each device and from company to company. Many other mechanical and electrical components are needed before HTS wire can be successfully incorporated into the devices discussed. For example, electrical connections and insulation must also be developed. Most importantly, the superconductor needs a refrigeration system.

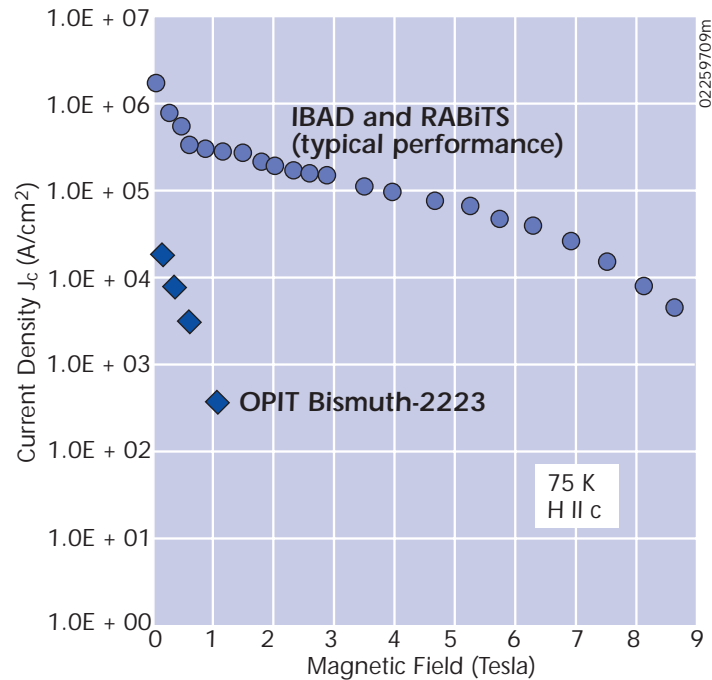
Cryogenic (low temperature) refrigeration techniques are used to reach the necessary temperatures. The colder the operating temperature, the more complex and expensive the technique. In addition, as temperature is lowered, the amount of energy needed to maintain that temperature increases dramatically. This is one strong technological factor favoring HTS devices: they require much simpler, cheaper, and more efficient cooling systems than their LTS cousins.

A car engine is cooled by pumping water through the engine where it absorbs heat. The water continues back out to the radiator where contact with outside air cools it down. Many HTS devices are cooled in the same way, by flooding the conductor with liquid nitrogen instead of water.



Future HTS cooling systems are expected to be trouble free and low maintenance. Engineers will likely modify the designs of existing devices like motors and transformers to operate with HTS components. In order to keep costs down, they are making use of parts that are already available. This is not always feasible; other devices do not have non-superconducting counterparts and must be designed and built from the ground up.

Designing and building an electric power device based on superconductors is a challenging proposition, with many complicating factors to be weighed and evaluated. Each manufacturer will likely develop proprietary methods to assemble their products in a cost-effective and commercially viable manner. ■



**Figure 7. IBAD, RABiTs, and OPIT Performance — Recently developed coated-conductor processing methods (RABiTS and IBAD) produce samples with better performance characteristics than bismuth OPIT wires.**

## Section IV. Electric Power Applications

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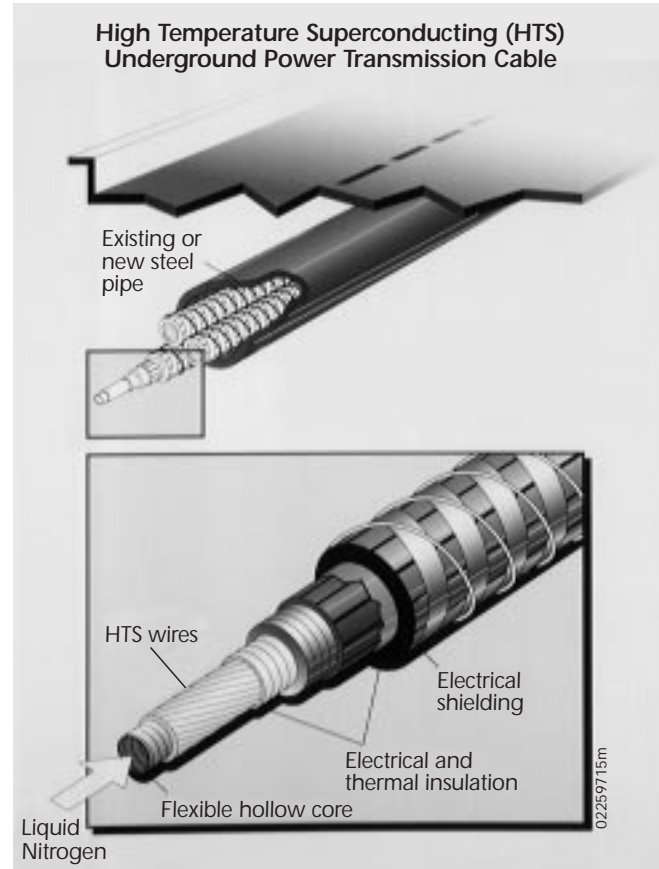
A variety of electric power applications for HTS wire are proposed or now in development. These applications have the potential to create a new, thriving industry that will serve large domestic and overseas markets. The electric power devices and components being designed to incorporate superconducting technology will operate more efficiently and less expensively than their conventional alternatives.

The potential of superconducting technology is awe-inspiring: power plants could generate electricity using less fuel and producing fewer emissions; electric motors could be smaller and much more powerful; power cables could transmit 3–5 times more electricity; and energy could be stored much more efficiently.

### How will HTS impact current superconductor applications?

Superconductivity has been in the marketplace for more than 20 years, in equipment such as MRIs, magnetic separators, magnets, NMR, and high-energy physics devices such as particle accelerators and in particle detectors used by astronomers.

HTS electric power equipment exhibits half the energy loss of typical power equipment.



Underground HTS cables can carry three to five times more current than conventional copper cables.

As mentioned in the previous sections, these systems are all built from LTS wire, which has met these needs very well. Manufacturers have begun considering ways HTS might improve the performance and lower the cost of these systems, which would continue to rely primarily on LTS wires for the near term. HTS is, of course, a long-term replacement candidate.

### Magnetic Resonance Imaging (MRI)

The core of an MRI machine is a powerful magnet. MRI systems built with HTS magnets could eventually be smaller and more powerful than is now possible with LTS-based systems. Further advances in MRI, made possible by HTS technology, would reduce costs, making medical imaging much more accessible.

In 1993, U.S. manufacturers shipped roughly 400 MRI machines having a total value of \$800 million. Unit prices range

# Applications

from \$1 million to as high as \$3 million, in sizes common in hospital and outpatient settings. Smaller, lower-cost units tend to dominate the market. If perfected, HTS technology could greatly expand this market.

### Magnetic Separators

The ability to selectively separate materials is very valuable to numerous industries. Magnetic separation techniques purify mixed materials with different magnetic properties. For example, the whitening agents for paper, kaolin clay, and for pigments,  $\text{TiO}_2$ , are purified in vast quantities by passing a mixture of unprocessed or unseparated material through the center of a large magnet. Material that is grey with impurities when it enters the separator is pure white when it exits.

A magnetic separator made with HTS coils would be more efficient than an LTS-based unit because of reduced cooling needs, and the larger magnetic fields created by HTS technology

would increase the processing rate. Converting to HTS components would make it feasible for dilute or less valuable ores to be processed profitably, and new types of material separations would be made possible.

### What are some HTS applications that are being developed now?

Applications incorporating HTS technology are poised to explode into the market over the next 10 years, impacting electronics, transportation, medicine, and many other industries as well. Market impact is difficult to estimate, but could parallel the explosive growth of fiber optics over the past 20 years. Several important new HTS electric power applications likely to emerge in the next decade are discussed below.

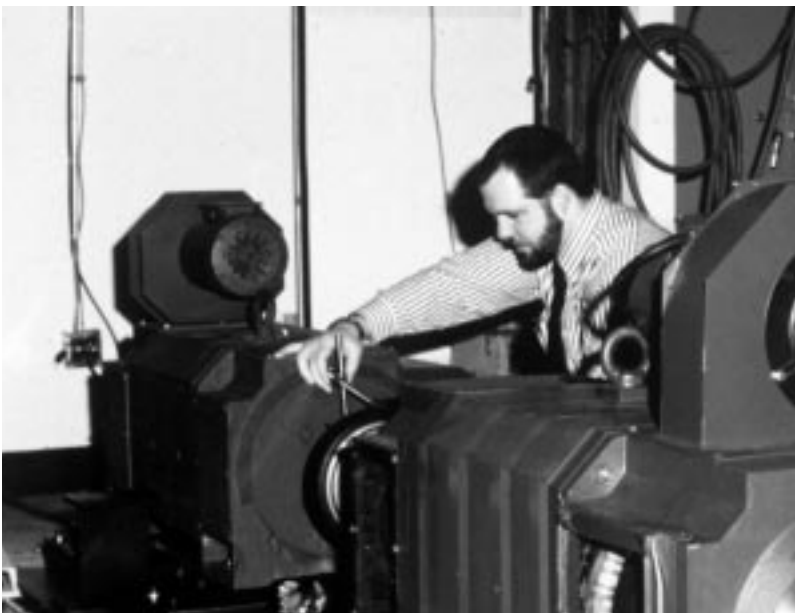
### Transmission Cables

Transmitting electricity is a natural fit for HTS technology. The dominant attraction of under-

ground HTS cables is that they can carry three to five times more current than conventional copper cables. Some HTS cable designs are based on retrofitting existing underground pipes that hold low-capacity conventional cables. In these systems, HTS wire is woven around a central pipe that carries liquid coolant. Multiple layers of thermal and electrical insulation protect the assembly. Old cable in many urban areas can be replaced with HTS cable, enabling increased power transmission through existing conduits. HTS cables may also be used in areas where overhead lines are rejected for environmental or aesthetic reasons.

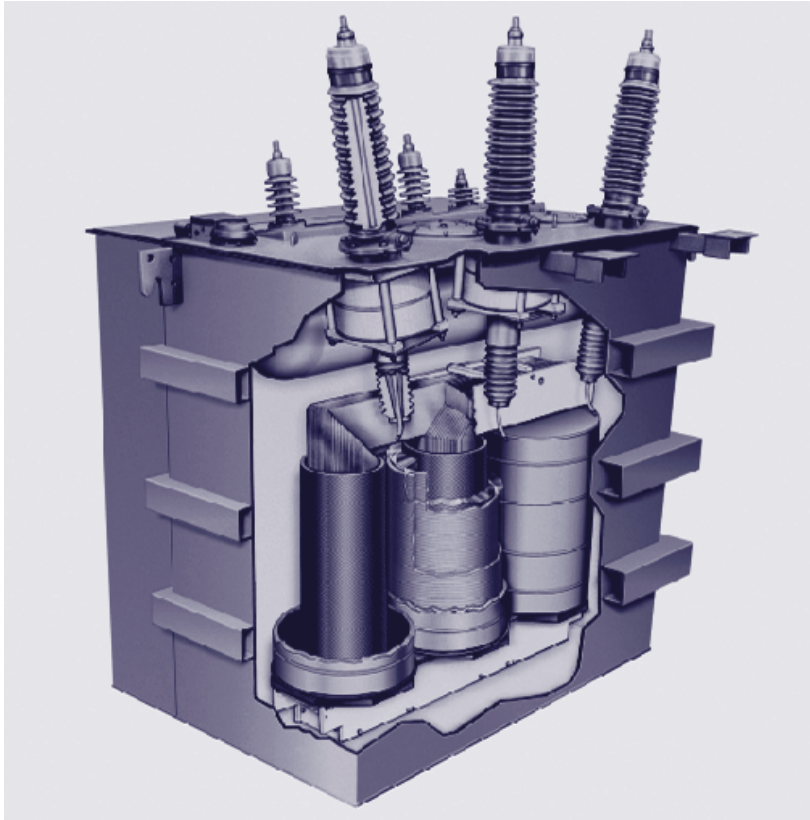
### Motors and Generators

In conventional motors and generators, magnetic fields are generated by large coils of copper or aluminum wire. HTS wire can carry much larger electrical currents, which means remarkably smaller and more powerful systems. For instance, a 1,000 horsepower HTS motor can be 50% smaller than a conventional motor of the same power. Manufacturing operations of all kinds could benefit from systems that take up less space and provide increased working capacity. In addition, substituting HTS wire for conventional wire eliminates energy loss due to electrical resistance, enabling motors and generators to operate with up to 98% and 99.5% efficiency, respectively. Today's typical generator operates at an efficiency rate of 97%–98%; a typical motor at 90%–96%.

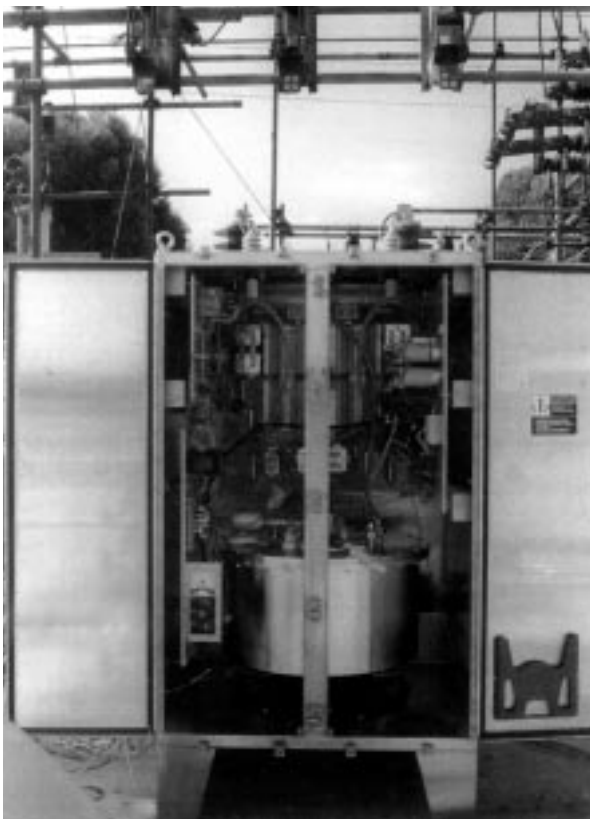


Reliance Electric Company/PIX03585

**Motors and generators that incorporate HTS wire are much smaller and more energy efficient than conventional systems.**



Waukesha Electric



Lockheed Martin/PX03582

**In an HTS transformer, energy losses can be cut by 50% by replacing copper wire with HTS wire. They are also about half the size, less noisy, and oil free, which eliminates the fire hazard of conventional transformers.**

### Transformers

Transformers are relatively simple devices. Their sole purpose is lowering or raising system voltages in order to transport electricity more efficiently. Voltages are raised or lowered by inducing a new current (and voltage) in one coil by the magnetic field of a second coil. Electricity generally passes through at least three transformers before it is used by a consumer; three to six percent of all generated electricity is lost to transformer inefficiencies. In an HTS transformer, coils will be made from HTS wire instead of copper, reducing these losses by

half. Additionally, HTS transformers will be as much as 50% smaller, and will no longer pose a fire hazard because they will not require flammable cooling oil. These are attractive benefits to utilities that have space limitations or want to increase their grid efficiency, as HTS-outfitted transformers can be placed closer to—even on top of or inside—buildings, relieving cramped substations.

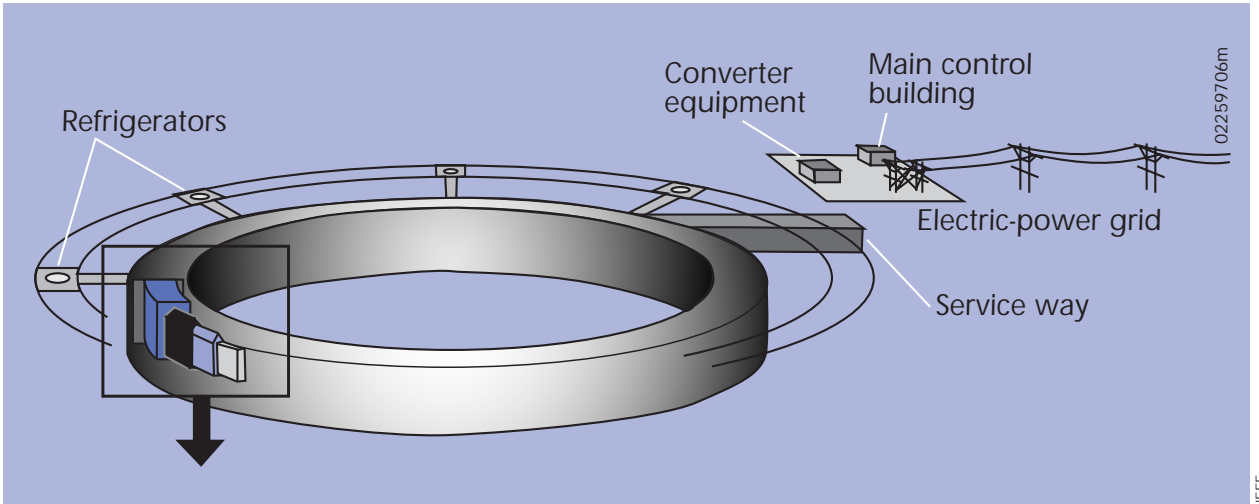
### Current Limiters

A current limiter protects against disturbances in otherwise smooth electricity delivery. Lightning or other accidents can send a surge of power through the utility grid that is beyond its capacity, and as a result, the grid's circuit breakers shut the system down to protect it from catastrophic damages. Utilities need new options to help them cope with these events.

HTS current limiters aren't designed to replace breakers, but to complement them. Strategically placed in the utility grid, these devices can effectively limit current spikes that are experienced by circuit breakers. One recent design for utility substation protection incorporates a large in-line HTS coil as an energy-absorbing device. When a large pulse or spike of current comes through the system, the HTS coil automatically absorbs the excess energy within a few milliseconds, therefore no equipment is exposed to the fault. Circuit breakers that would ordinarily trip, don't, and the entire system operates as if no current spike had existed. This protection allows utilities to increase system loads and to provide more reliable service to consumers.

**HTS current limiters absorb current spikes that are experienced by utility equipment—allowing increased system loads and more reliable service to consumers.**





**Superconducting magnetic energy storage (SMES) is one of the possible applications for HTS. Current circulates with no resistance in a superconducting ring, installed below the ground.**

## Magnetic Energy Storage

One shortcoming of the modern utility grid is its inflexibility; once manufactured, electricity must be used immediately. There is no pool of electricity available to accommodate momentary or long-term surges in demand. Accordingly, generators must be held on standby or started up for periods of excessive electricity demand, which is highly inefficient.

New techniques based on superconductivity offer solutions to the problem. Energy storage depots can be created, which

allow electricity to be deposited or withdrawn depending on circumstances. Utilities have recently identified distribution substations as valuable locations for these depots. Other customers have identified the need to protect sensitive equipment from momentary disturbances in power supply.

Two approaches are currently being investigated: one based on flywheels and the other on magnetic fields. Flywheel energy storage devices rely on spinning discs that float on superconducting magnets and store energy in the motion of their rotation. Once charged, these discs will spin

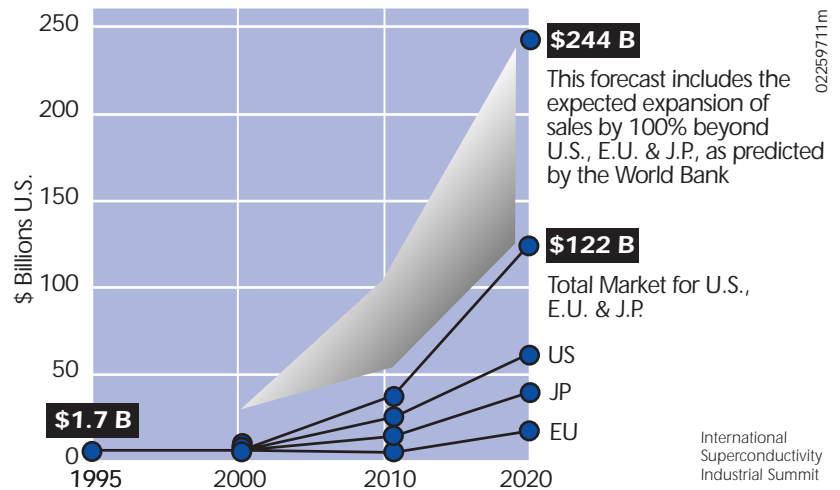
almost indefinitely, without losing any of their energy to friction.

Another storage technique, superconducting magnetic energy storage, relies on large superconducting coils to store energy as a powerful magnetic field. The major benefits of these systems is that they have energy efficiency rates in excess of 90%, as compared to batteries, which have limited lifetimes, and efficiency rates of only 80%–90%. If these superconducting techniques are perfected, the energy storage industry could be revolutionized. ■

HTS technology has made great strides in recent years, amazing those who have followed its progress and witnessed the development of HTS motors, power cables, and other electrical devices. Creative solutions have been found to the seemingly intractable problem of making usable electrical wires from the difficult and brittle ceramic HTS materials. New processes have been invented that promise higher-performance, lower-cost HTS wires in the not-too-distant future.

Meanwhile, breakthrough designs have led to the construction and testing of first-of-its-kind prototype HTS transformers, magnetic separators, motors, power cables, and current controllers. These successes have, in turn, led to the development of pre-commercial prototypes.

The payoff of continued investment promises to be substantial. In 1993, the International Superconductivity Industry Summit, estimated the international market for superconductor electric power devices will grow to \$32 billion by 2020. The entire superconducting market, which includes applications in the transportation, medical, electronics, and scientific



**Figure 8. Worldwide Market for all Superconductor Applications — The International Superconductivity Industrial Summit predicted a worldwide market for superconductor-based products and systems of \$122 billion by 2020.**

research industries, is estimated to be between \$100 billion and \$200 billion by 2020. **Figure 8** includes the World Bank forecast, which predicts a market as large as \$244 billion.

The potential benefits and the promise of vast global markets drive investment in superconductor technology. It is imperative that resources remain focused on creating robust HTS wire with high performance and developing reliable and efficient electric power systems that address the

needs of electric utilities and U.S. consumers.

Superconductivity is often compared to fiber optics, which revolutionized the communications industry, and even to transistors, without which we would not have things like digital watches and personal computers. The capacity of these discoveries to transform our world far surpassed any applications we could have dreamed of. Superconductivity, too, will surely continue to fuel our imaginations.

The first decade of HTS technology achieved breakthroughs more quickly than most would have predicted; the next decade will likely boast developments just as exciting and unexpected. The progress thus far is inspiring: world-record current densities and wire lengths, increasing operating temperatures, and innovative design prototypes. HTS electric power applications will make an indelible impression on the future global market, impacting a large cross section of industry and improving the quality of our lives. ■

The Future

superconducting applications now being developed will lead us into the 21<sup>st</sup> century.

## For More Information on Superconductivity

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### **American Superconductor Corporation**

508-836-4200

<http://amsuper.com/>

### **Applied Superconductivity Center**

University of Wisconsin

608-263-5029

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### **Argonne National Laboratory**

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### **Science and Technology Center for Superconductivity**

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